

## CESIUM ATOMIC FOUNTAIN CLOCKS AT NMIJ

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### Abstract

*We describe the recent progress in our cesium atomic fountains at National Metrology Institute of Japan (NMIJ). We have developed three atomic fountains: NMIJ-F1, NMIJ-F2, and a truncated atomic beam fountain. NMIJ-F1 has been the primary frequency standard with uncertainty of  $4 \times 10^{-15}$  since 2004. Especially in the last 4 years, we have reported the data to Bureau International des Poids et Mesures (BIPM) 21 times by operating NMIJ-F1 due to the progress in the stability and the reliability of the whole system. The second atomic fountain, NMIJ-F2, is under construction to achieve uncertainty of less than  $1 \times 10^{-15}$ . The optical molasses for generation of cold atoms is composed of six horizontal laser beams and two vertical laser beams with power of about 100 mW per beam. In addition, we proposed the truncated atomic beam fountain to achieve both a low collisional frequency shift and high frequency stability.*

## INTRODUCTION

Cesium atomic fountains have been employed as primary frequency standards for calibration of International Atomic Time (TAI) [1]. In several atomic fountains, the uncertainty currently reaches the order of  $10^{-16}$ . On the other hand, the optical frequency standards, such as the optical lattice clocks [2] and the ion trap clocks [3], have been rapidly developed and declared the uncertainty less than that in a cesium atomic fountain. There is the possibility of redefinition of a second. For the redefinition, it is necessary that the optical frequency standards will be compared with the atomic fountains as accurately as possible.

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For both the contribution to TAI and the redefinition of a second, it is desired that the frequency measurement with a small uncertainty is performed on demand. Under the requirement, we have developed NMIJ-F1 and NMIJ-F2. Whereas NMIJ-F1 has been already used for the reports to BIPM with an uncertainty of  $4 \times 10^{-15}$  since 2004 [4], NMIJ-F2 is now under construction. For NMIJ-F1, we mainly improve the stability and the reliability of the fountain system for frequent reports. On the other hand, NMIJ-F2 has been developed to obtain uncertainty of less than  $1 \times 10^{-15}$ .

On the other hand, to improve the uncertainty to  $1 \times 10^{-16}$  or less, the suppression of the collisional shift maintaining the frequency stability is one of the important issues. Although several approaches, such as juggling [5,6], a continuous fountain [7], an adiabatic passage method [8], and cancellation of collisional shift [9], have been attempted, we proposed a truncated atomic beam fountain as an alternative method, where a cold atomic beam is launched up and turned off before the top of the atomic beam arrives at the Ramsey cavity [10]. In this fountain, the cold atomic cloud made by the truncation of a cold atomic beam can be long in the vertical direction, so that the atomic density can be small without sacrificing the number of detected atoms. Moreover, like the juggling fountain, the atoms can be concentrated at the detection region by smoothly changing the launching velocity. We recently started the experiment of the truncated atomic beam fountain.

Figure 1 shows the relation between the atomic fountains and optical lattice clocks at NMIJ. For development of precise clocks, another clock as a reference is necessary for comparison. NMIJ-F1 will be used as a reference for NMIJ-F2 and the optical lattice clocks. Although NMIJ-F1 has a relatively large uncertainty, it will be employed at the time when the reference for NMIJ-F2 and the optical lattice clocks are necessary. NMIJ-F2 will be used as more precise reference for the optical lattice clocks. The experimental setup for the truncated atomic beam fountain is built for the proof of principle, and the data obtained are used for the improvement of NMIJ-F2.

In this paper, we describe the recent progress of the three atomic fountains at NMIJ. For NMIJ-F1, we show the long-term data. Next, we show the current status of the development of NMIJ-F2. Then, we explain the principle of the truncated atomic beam fountain and make a theoretical calculation about the atomic density. Finally, we finish with a summary.

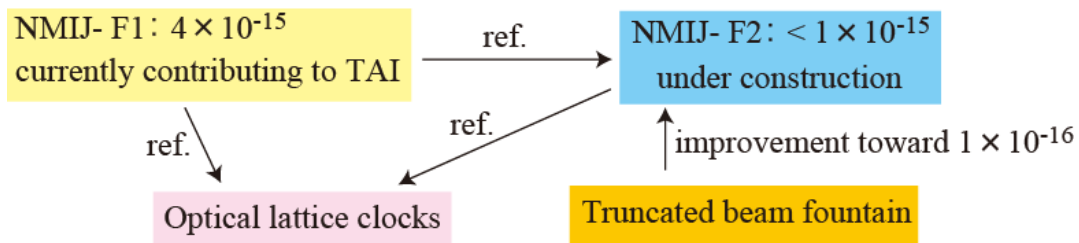


Figure 1. Relation between the atomic fountains and optical lattice clocks at NMIJ.

## NMIJ-F1

NMIJ-F1 is a common atomic fountain with optical molasses with a (001) configuration. Two

microwave cavities are put in the vacuum chamber, where one of the cavities is used to select the state  $F = 3$ ,  $m_F = 0$  of  $^{133}\text{Cs}$  atoms, and the other is employed for  $\pi/2$ -pulses for the Ramsey resonance. The frequency stability is typically  $8 \times 10^{-13} \tau^{-1/2}$ , where  $\tau$  is the averaging time. The type B uncertainty is estimated at  $3.9 \times 10^{-15}$ .

To improve the reliability, we modify the laser amplifier system and examine the shutter timing and jitter. Although we took the injection locking into a laser diode to amplify the optical power of an external-cavity diode laser, we now use two taper-amplifiers to obtain more stable phase-lock. Due to the amplification, the horizontal cooling beams and the vertical cooling beams have power of 25 mW and 10 mW per beam, respectively.

Figure 2 shows the data reported to BIPM in the last 4 years, where the blue dots and the red dots represent NMIJ-F1's data and the primary frequency standards (PFSs) taking TAI as a reference, respectively. As shown in Fig. 2, there were 21 time reports with agreement with the PFS mostly within the uncertainty in the last 4 years. Especially during MJD 54504–55039 (about 20 months), there were 14 time reports. In addition, the NMIJ-F1's data have been consistent with the PFSs. Although we did not report to BIPM during MJD 55040–55348 due to a trouble of the electric power system, we recovered from the trouble and started the reports again from MJD 55349.

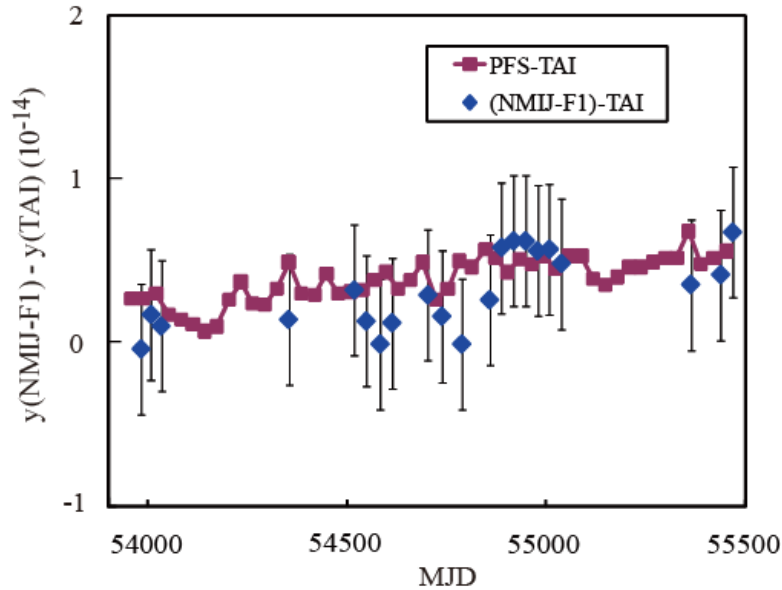


Figure 2. The long-term data of NMIJ-F1 reported to BIPM.

## NMIJ-F2

NMIJ-F2 has the two microwave cavities which are part of the vacuum vessel [11]. Due to these cavities, the uncertainty caused by microwave power dependence can be decreased, since the leakage of the microwave can be precisely estimated. In addition, the vacuum chamber at the trapping part has ports to introduce cooling laser beams for optical molasses with a (111) configuration. Compared with a (001) configuration, the diameters of cooling laser beams are not restricted by the 1-cm inner diameter of the microwave cavities, so that the number of cold atoms can be increased. In addition, one

taper-amplifier with output power of 500 mW is used for one cooling-laser-beam. Taking into account the decrease of the power through the double-path acoustic optical modulator and the coupling into the optical fiber, a power of 100 mW can be obtained per beam.

We launched up cold atoms with moving molasses with a (111) configuration. Figure 3 shows the time-of-flight signals 30 cm above the optical molasses. Here, Fig. 3(a) and 3(b) represent the signal caused by the cold atoms going upward and the signal due to the cold atoms going downward, respectively. From these two signals, the temperature of cold atoms is estimated at 120  $\mu$ K. This temperature is too high for the cold atoms to efficiently pass through the microwave cavities. In practice, the temperature of cold atoms in the typical atomic fountains is around 1  $\mu$ K.

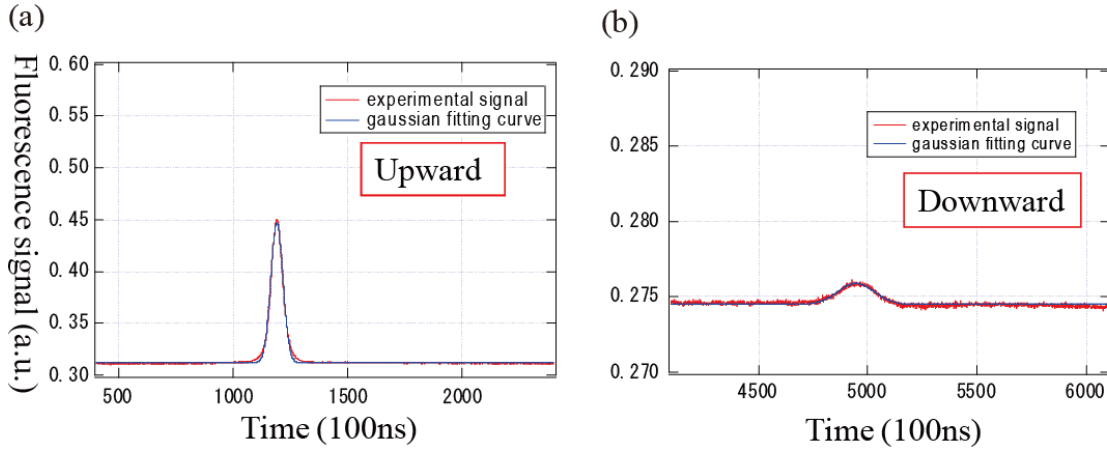


Figure 3. Time of flight signals when the cold atoms are launched up with the optical molasses with a (111) configuration.

To examine the causes of the high temperature, we applied these cooling laser beams to NMIJ-F1 with optical molasses with a (001) configuration. The cooling laser beams can be carried through optical fibers from the optical bench for NMIJ-F2 to the vicinity of the vacuum chamber for NMIJ-F1 without changing the optical alignment. As a result, NMIJ-F1 worked well. Therefore, we found that the optical system such as laser frequency control and switching worked well, but the alignment of the (111) configuration was not completed.

While the cold atoms are launched up along the vertical laser beams in a (001) configuration, the launching direction is different from any cooling laser beam in a (111) configuration. This should make the difference in the complexity of the alignment. Since the optical system for NMIJ-F2 worked for a (001) configuration, we will build NMIJ-F2 with vertical cooling beams at first. Here, the optical molasses is composed of six horizontal beams (crossing angle: 60 degrees) and two vertical beams due to the restriction of the optical access for the trapping chamber.

For the modification, the vacuum chamber was opened to change the arrangement of the viewports. Making the vacuum and baking the chamber have been done to get a pressure of  $\sim 10^{-7}$  Pa. During the baking, robust and convenient jigs for optics around the vacuum chamber were designed and produced. Moreover, the vertical axis was precisely aligned by a guiding laser shone upward whose direction is

adjusted with a setup with a hung weight. The experiment on launching cold atoms will start again soon.

## TRUNCATED ATOMIC BEAM FOUNTAIN

Figure 4 schematically shows the principle of the truncated atomic beam fountain. First, as shown in Fig. 4(a), a cold cesium atomic beam in the state  $6^2S_{1/2}$ ,  $F = 4$  is launched by continuously moving molasses [12]. Furthermore, additional transverse polarization-gradient cooling to a temperature of about  $1\ \mu\text{K}$  is performed with four horizontal cooling laser beams shone orthogonally to each other to reduce the loss of atoms due to the restricted inner diameters of the microwave cavities. In a state-selection cavity, to select the sublevel  $m_F = 0$  to remove the first-order Zeeman shift, the sublevels are split by a weak magnetic field, and atoms in the state  $6^2S_{1/2}$ ,  $F = 4$ ,  $m_F = 0$  are transferred to the state  $6^2S_{1/2}$ ,  $F = 3$ ,  $m_F = 0$  with a  $\pi$ -pulse microwave.

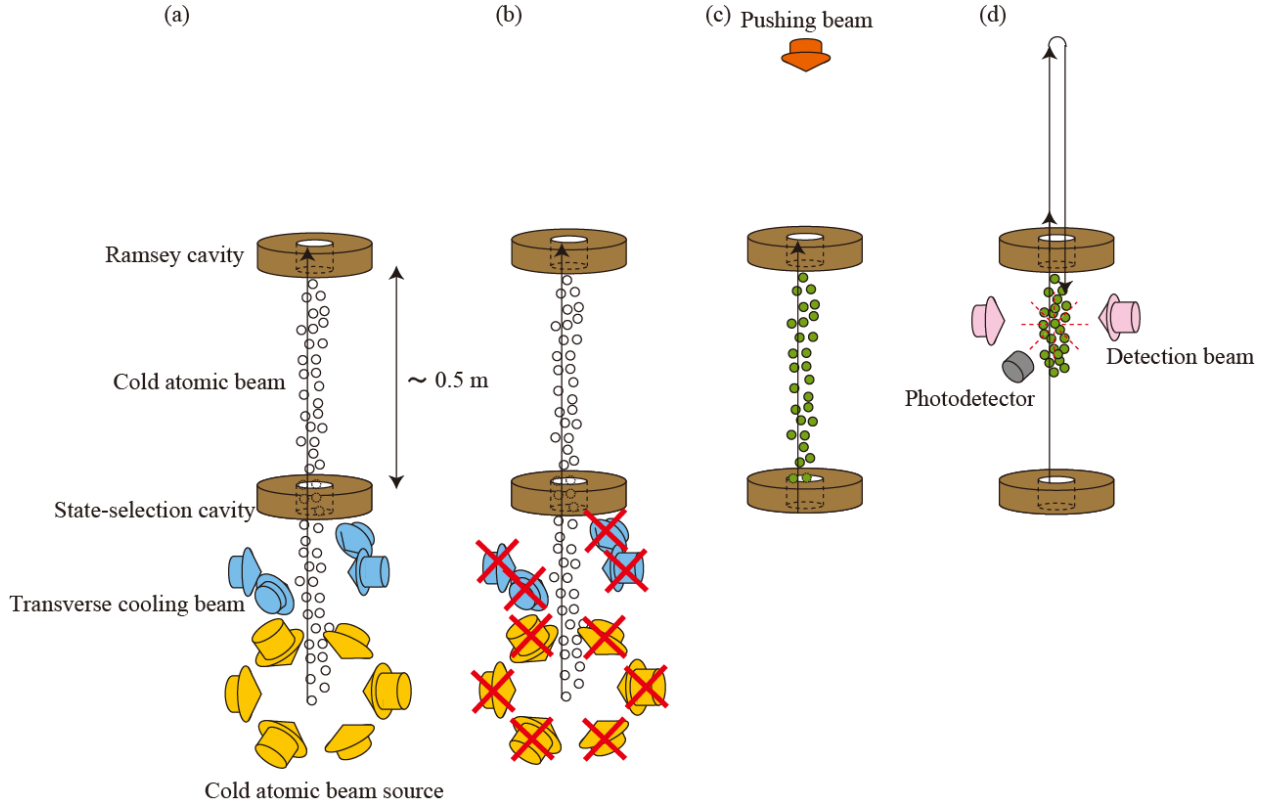


Figure 4. The principle of the truncated atomic beam fountain is schematically shown.

As shown in Fig. 4(b), the laser beams comprising the cold atomic beam source and the transverse cooling are turned off before the top of the cold atomic beam reaches the Ramsey cavity. Then, as shown in Fig. 4(c), a laser beam tuned to the transition  $6^2S_{1/2}$ ,  $F = 4 - 6^2P_{3/2}$ ,  $F' = 5$  is momentarily shone vertically downward to repel atoms in the state  $6^2S_{1/2}$ ,  $F = 4$ . As a result, atoms in the state  $6^2S_{1/2}$ ,  $F = 3$ ,  $m_F = 0$  remain between the state-selection cavity and the Ramsey cavity. Afterward, similarly to in an

ordinary atomic fountain, two  $\pi/2$ -pulse microwaves with an interval of  $\sim 1$  s are applied to measure the resonant frequency of the transition  $6^2S_{1/2}, F = 3, m_F = 0 - 6^2S_{1/2}, F = 4, m_F = 0$  using the Ramsey resonance. As shown in Fig. 4(d), the number of atoms is state-selectively estimated by observing fluorescence in the detection region, and the probability of the transition into the state  $6^2S_{1/2}, F = 4, m_F = 0$  through the Ramsey resonance is evaluated.

The advantages in the truncated atomic beam fountain are in four parts: (1) A thin and long atomic cloud can be generated. (2) No cooling laser beams are shone during the interrogation. (3) The launching velocity can be swept by smoothly changing the frequency of the upward cooling beams and the downward cooling beams. (4) The system is highly compatible with the common fountain system.

The first advantage contributes to both a low atomic density and the large number of detected atoms, that is to say, both suppression of the collisional shift and improvement of the frequency stability. The length of the truncated beam is restricted to the distance between the cavities. Considering practically, the distance can be 0.5 m, so that the initial volume of the cold atomic cloud can be one degree of magnitude bigger than that in the common optical molasses.

The second advantage causes the suppression of a light shift by residual scattering light originating from the cooling laser beams. The cooling laser beams are shone for the continuous fountain and the juggling fountain when atoms are interrogated. Compared with these methods, the light shift can be readily suppressed in the truncated atomic beam fountain.

Due to the third advantage, the concentration of atomic density at the apogee can be avoided while a large atomic density at the detection region can be obtained (see the following).

Due to the fourth advantage, the truncated atomic beam fountain can be relatively easily tried, since the cold atomic beam source can be made with optical molasses with a (011) configuration and a (111) configuration. Note that a (001) configuration cannot be applied to the truncated atomic beam fountain, since the cold atomic beam is interrupted by the vertical cooling beams. In addition, a longer distance between the cavities is more suitable for the truncated beam fountain.

We theoretically estimated the atomic density as a function of time  $t$  as shown in Fig. 5. Here, the cold cesium atoms are launched up with an initial velocity  $v_L(t_0) = v_0 - agt_0$  at time  $t_0$ , where we take  $-0.05 \text{ s} < t_0 < 0.05 \text{ s}$  and  $v_0 = 4.4 \text{ m/s}$  (launching height: 1 m). The parameter  $a$  is called the sweeping parameter in the following, and  $g$  is the acceleration due to gravity. The cold atomic beam has a constant flux  $f = 1 \times 10^8 \text{ s}^{-1}$ , the lateral radius ( $e^{-1/2}$ )  $r_0 = 6.3 \text{ mm}$ , the transverse temperature  $T_r = 1 \text{ } \mu\text{K}$ , and the longitudinal temperature  $T_z = 70 \text{ } \mu\text{K}$ . The orange line, the red line, and the blue line in Fig. 5 show the atomic density when  $a = 0, 1/2$ , and 1, respectively. Moreover, the green zone indicates the interrogation time when the Ramsey cavity is located 0.5 m above the cold atomic beam source. On the other hand, the vertical red line shows the detection time. The details are described in Ref. [10].

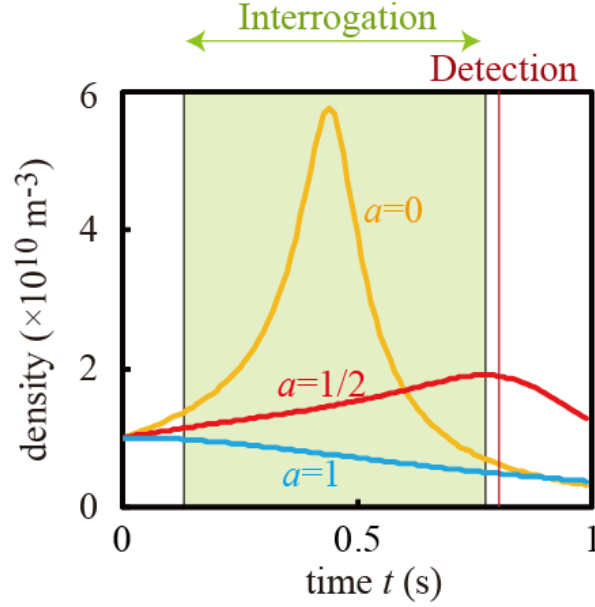


Figure 5. The atomic density in the truncated atomic beam fountain as a function of time  $t$ .

When  $a = 0$ , atoms are launched up with the constant launching velocity. When  $a = 1/2$ , the atomic density becomes large at the detection region like the juggling fountain. On the other hand, when  $a = 1$ , there is no relative velocity between the atoms if not considering the thermal expansion.

As shown in Fig. 5, while the atoms concentrate around the apogee at  $a = 0$ , the atomic density in the interrogation region can be suppressed by sweeping the launching velocity. Especially when  $a = 1/2$ , the atomic density in the detection region can be increased. Therefore, we can make the collisional shift smaller while the signal-to-noise ratio can be enhanced. Compared with PTB-CSF2 [13], which was developed with optical molasses the most recently, it is theoretically estimated that the collisional shift becomes smaller by a factor of 13 with the same frequency stability.

## SUMMARY

We have developed three atomic fountains at NMIJ. NMIJ-F1 is operating, but NMIJ-F2 and the truncated atomic beam fountain are under construction. In NMIJ-F1, we guide the long-term operation, and we have reported 21 times to BIPM in the last 4 years. In NMIJ-F2, we aim the uncertainty of less than  $1 \times 10^{-15}$ , where we use microwave cavities which are part of the vacuum vessel and the optical molasses with the six horizontal laser beams and the two vertical laser beams with power of 100 mW per beam. The truncated atomic beam fountain was proposed for the suppression of the collisional shift without sacrificing the frequency stability. The experiment is now in progress.

In the near future, we will complete NMIJ-F2 and do the experiment of the truncated atomic beam fountain.

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